Collaborative Immersive Analytics

Mark Billinghurst, Maxime Cordeil, Anastasia Bezerianos, Todd Margolis

8. Collaborative Immersive Analytics

Mark Billinghurst[1], Maxime Cordeil[2], Anastasia Bezerianos[3], and Todd Margolis[4]

[1] School of ITMS, University of South Australia, Mawson Lakes, Australia
mark.billinghurst@unisa.edu.au
[2] Monash University, Australia
max.cordeil@monash.edu
[3] Univ. Paris-Sud, CNRS, Inria, Université Paris-Saclay, France
anastasia.bezerianos@u-psud.fr
[4] Qlik, California USA
tmargo@gmail.com

Abstract. Many of the problems being addressed by Immersive Analytics require groups of people to solve. This chapter introduces the concept of Collaborative Immersive Analytics (CIA) and reviews how immersive technologies can be combined with Visual Analytics to facilitate co-located and remote collaboration. We provide a definition of Collaborative Immersive Analytics and then an overview of the different types of possible collaboration. The chapter also discusses the various roles in collaborative systems, and how to support shared interaction with the data being presented. Finally, we summarize the opportunities for future research in this domain. The aim of the chapter is to provide enough of an introduction to CIA and key directions for future research, so that practitioners will be able to begin working in the field.

Keywords: collaborative immersive analytics, immersive analytics, immersion, human-computer interaction, visual analytics, collaboration, collaborative visualization, shared interaction

8.1. Introduction

In a world of increasing computing power and sensing, there is more data being generated than ever before. Over the last ten years Big Data [95] has become an important field of research with data scientists exploring many different ways to transform terabytes of information into valuable insights. One of the popular methods for creating understanding is to generate visual representations of the data, as explored in the area of Visual Analytics [125], defined as "the science of analytical reasoning facilitated by interactive visual interfaces". In this case a wide variety of visualization techniques are used to explore complex datasets. For example, 2D bar charts can be used to understand detailed election results and 3D graphics to show sensor data on terrain models. Visualization tools have been shown to improve performance time and productivity on a range of different tasks such as software analysis [50], data analysis [118], and information retrieval [130], among others. Sun *et al.* [119] provide an excellent summary of visual analytics techniques and applications, and their benefits.

Most recently, researchers have begun to explore how novel immersive display technology can be used to enhance visual analytics solutions (Chapter **??**). The term Immersive Analytics [20] was coined to describe "an emerging research thrust investigating how new interaction and display technologies can be used to support analytical reasoning and decision making". These display technologies range from room scale immersive CAVE projection systems [30] to Virtual Reality head mounted displays (HMDs) [31], and from interactive walls, tables and multi-display environments [124] to portable head worn Augmented Reality displays [3]. Klapperstück *et al.* [72] proposed ContextuWall, a system for interactive local and remote collaboration using touch and mobile devices as well as displays of various sizes. Emerging interaction technologies include devices like the Microsoft Kinect [71] or Leap Motion [74] which support natural gesture input, eye-tracking devices [99] for collecting awareness information, and even Brain Computer Interfaces that respond to thoughts [87].

Previous research has shown that using Immersive Analytics technologies can enable people to be significantly more effective at understanding data visualizations than more traditional interface technologies. For example, Belcher *et al.* found that using Augmented Reality (AR) improved user performance at finding node connections in complex graph visualizations compared to a 2D desktop presentation [8]. Similarly, Ware [135] found that using head-coupled stereo viewing enabled a person to understand an abstract graph three times the size of a graph viewed on a normal non-stereo monitor.

However, effective presentation on immersive displays is only one way to gain an understanding of complex data. Research stretching back over decades has found that collaborative decision making is often more effective than working on problems alone. Hill [51] provides a good review of early research comparing group versus individual performance on different tasks, finding that group performance is generally superior to that of an average individual. Similarly, in comparing collaborative to single user performance on an information visualization task, Mark *et al.* [83] found that groups worked slower, but produced more accurate results. Recently, Woolley *et al.* [137] have argued for a group collective intelligence factor that predicts performance on collaborative tasks, and could be improved by using collaborative tools. However, supporting effective collaboration can be challenging and was identified as one of the Grand Challenges for Visual Analytics [27].

Co-located collaboration provides important benefits. Sawyer *et al.* showed that team rooms supporting face-to-face activities helped focus the activities of work groups and removed them from interruptions [108]. Most recently, Teasley *et al.* found that co-located software teams working in "war rooms" with access to tools such as computers, whiteboards and flipcharts were twice as productive as the similar teams working in a traditional office environment [123]. Some visualization systems, such as CoVis [33] have specific tools for supporting co-located collaboration.

Significant benefits can be found from teams working together in an Immersive Analytics setting. Marai *et al.* [82] review three Immersive Analytics projects undertaken by research teams using the CAVE2 immersive projection environment (see Figure 1). The feedback was overwhelmingly positive, with the authors saying, "At the end of the meeting one of the team members said that the team got more done in 2 days than in 6 months of email, Skype, and Google Hangout." They were able to make such rapid progress because the CAVE2 environment enabled a group of people to work together face to face while seeing multiple representations of the data across a large amount of screen real-estate all at the same time. This research builds on their earlier work with the Cyber-Commons [76] which was a 100 megapixel tiled display wall that allowed small groups of multidisciplinary researchers to work together.

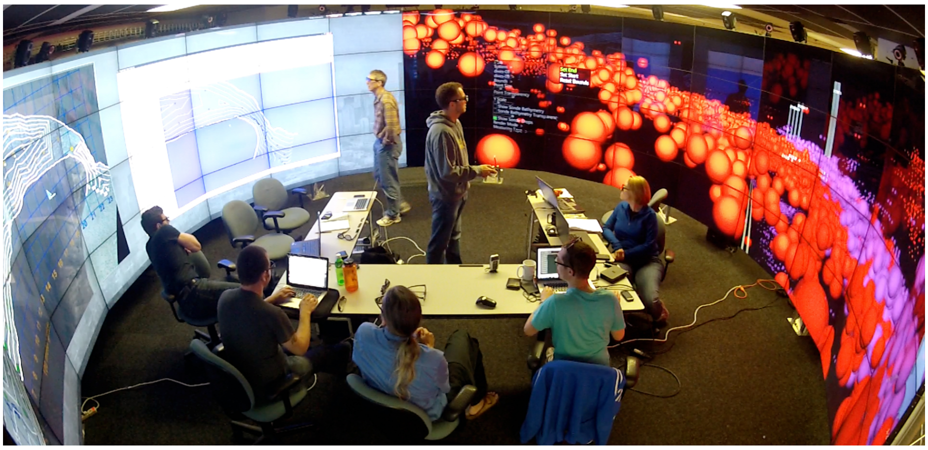

Fig. 1: EVL researchers at work in the CAVE2 at UIC, from [82]

In this chapter we provide an overview of and introduction to Collaborative Immersive Analytics. Although there has been a significant amount of research on how immersive technologies can support collaboration, there has been very little research in the newer area of Collaborative Immersive Analytics. Our aim is to provide an introduction to researchers to this field, describe some example applications, provide design guidelines, and clearly identify directions for future research. This should be helpful for guiding researchers wanting to enter this emerging field of research or for teams requiring new means of analysis for complex data.

In the remainder of the chapter we first provide a definition of Collaborative Immersive Analytics, and various roles people have when using collaborative systems. We then provide an overview of collaborative interaction methods, before identifying promising areas for research. Finally, we summarize the chapter and outside areas for future work. Overall, the aim of this chapter is to provide enough of an introduction to Collaborative Immersive Analytics that interested readers could begin to do their own work in the field.

8.2. Definition and Scope

Before we can discuss Collaborative Immersive Analytics (CIA) we need to define what the term means and describe the overall scope of the chapter. CIA is so new that there is no well accepted definition. However Collaborative Immersive Analytics is related to Collaborative Visualization, a term that Isenberg *et al.* [58] define as:

The shared use of computer-supported, (interactive,) visual representations of data by more than one person with the common goal of contribution to joint information processing activities.

Using this definition, Isenberg points out that collaborative visualization lies at the intersection of the two major research fields of visualization and computer supported collaborative work (CSCW), each of which have made significant research contributions that could benefit collaborative visualization.

Considering this and returning to the original definition of Immersive Analytics, we define Collaborative Immersive Analytics as: *The shared use of immersive interaction and display technologies by more than one person for supporting collaborative analytical reasoning and decision making.*

The main difference between Collaborative Immersive Analytics and Collaborative Visualization is the focus in CIA on the use of immersive interaction and display technologies. Hackathorn and Margolis [45] point out that Immersive Analytics environments can span most of Milgram's Reality-Virtuality (RV) continuum [86]. The RV continuum is a well-known way of classifying interface technologies in terms of how they connect the physical and virtual worlds, from the fully physical world (on the left) to the fully virtual world (on the right) (Figure 2). Within this continuum is the class of Mixed Reality technologies which merge real and virtual worlds. This ranges from tabletop displays and Augmented Reality environments to fully immersive virtual reality head mounted displays and rooms.

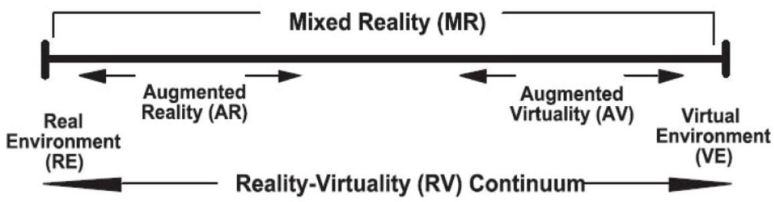

Fig. 2: Milgram's Mixed Reality Continuum, from [86].

Collaborative Immersive Analytics explores how Mixed Reality technologies such as these can be used in a collaborative setting. In contrast, Collaborative Visualization is concerned more with shared visualization in general, so the field of CIA can be viewed as a subset of the broader field of Collaborative Visualization. Just as Collaborative Visualization lies at the intersection of the field of visualization and CSCW, Collaborative Immersive Analytics lies at the intersection of Collaborative Visualization and Mixed Reality (see Figure 3).

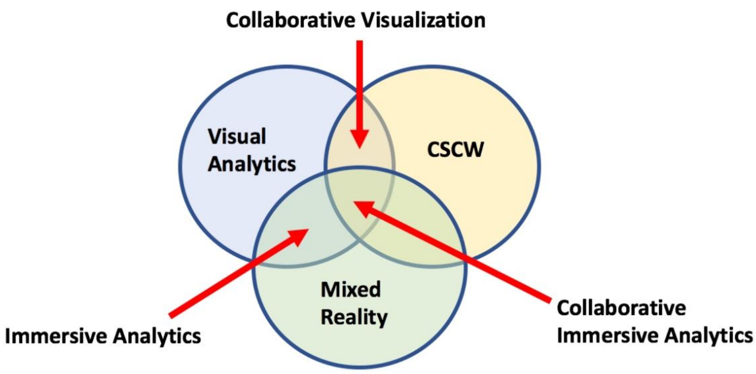

Fig. 3: The relationship between Collaborative Immersive Analytics, Collaborative Visualization and Immersive Analytics.

By its very nature, CIA is a multi-disciplinary research field. In addition to Collaborative Visualization, it is also related to the fields of Scientific Visualisation (SciVis) [68], Information Visualisation (InfoVis) [17] and Visual Analytics [125], all of which are well established with ongoing conferences and journals over the past 20 years. However, in these fields relatively little attention has been paid to the study of collaborative visualisation, especially using advanced interface tools. For example, Isenberg points out that of the nearly 1600 papers published in the three main IEEE visualization conferences from 1990 to 2010, only 34 focused on collaborative visualisation, less than three percent of the total [58]. According to Google Scholar, until now there have been no papers published using the term "Collaborative Immersive Analytics".

This lack of research means there are significant opportunities for research in the field of Collaborative Immersive Analytics. The focus of this chapter highlights these areas and provides some of the background material to help interested researchers. We provide some important background work in collaborative systems, discuss multi-user interaction modalities, highlight lessons learned from collaboration with immersive technologies such as Virtual and Augmented Reality displays and interactive walls and tables, and specifically identify important research topics. We should note that this chapter is not an exhaustive literature review, nor a tutorial on collaborative technologies or immersive interfaces in general.

In the next section we begin by introducing a taxonomy of collaborative systems based on space and time, and examples of collaborative immersive technologies that fit into this taxonomy. Then, we discuss the different roles that people have in collaborative systems and how they can interact with the datasets. Finally, we provide a high-level overview of some of the possible research opportunities that could be explored in the future.

8.3. Collaboration Over Space and Time

Using Immersive Analytics technology there are many different types of collaboration possible. For example, analysts can work together face to face in a CAVE [82] or a multi-display environment [124], come together from remote locations into the same shared VR environment [77], or leave annotations in datasets to be viewed at different times [35]. Collaborative scenarios like these can be classified according to where they occur in space (distributed vs. co-located) and time (synchronous vs. asynchronous) [65] (see Figure 4). For example, people working together in a lab space are in a Synchronous/Co-located configuration, while those exchanging email over time are working in a Distributed/Asynchronous configuration.

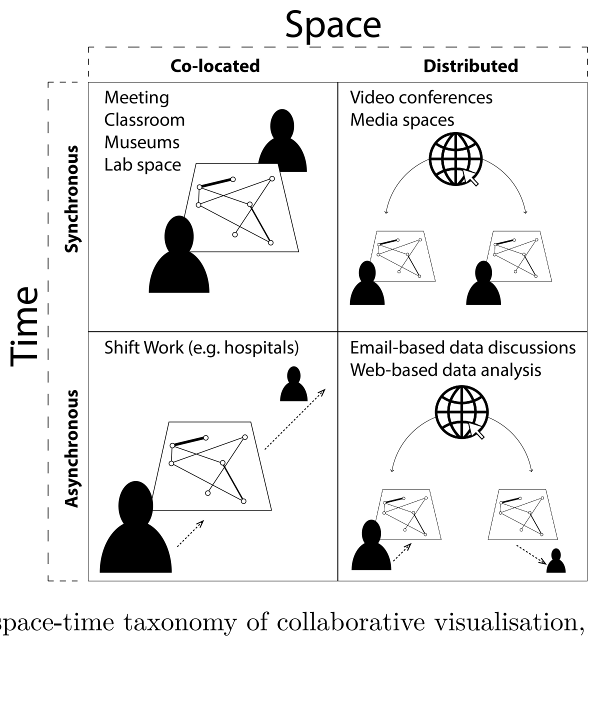

Fig. 4: A space-time taxonomy of collaborative visualisation, from [58].

In this section we describe this classification in more detail and review several examples of CIA systems at different points in the space/time collaborative matrix. We also describe some of the lessons that have been learned from previous research that can be used as guidelines for developing collaborative systems.

8.3.1. Co-Located Synchronous Collaboration

There are many examples of Immersive Analytics applications where collaborators are in the same physical space and working together at the same time. Marai *et al.* [82] describes three Immersive Analytics projects where a small group of researchers work face-to-face together inside the CAVE2 environment surrounded by immersive projection screens. In this case researchers brought their own laptop computers into the CAVE2 and were able to work on their private displays as well as use the shared immersive display. Other environments include shared visualizations on interactive tabletops where people stand around the table surface [70] [1], responsive wall displays that multiple people can interact with at the same time [23] [29] [2] [5], and face to face collaborative AR solutions [109] [12]. Figure 5 shows a typical use of interactive tables and walls to support face-to-face collaboration.

Fig. 5: Examples of using interactive wall displays and tabletops for co-located synchronous collaborative visualization.

Co-located synchronous collaboration has a number of advantages. Collaborators can directly see one another and work together at the same time and so changes they make to the data set can be easily seen by their co-workers [115]. This makes it very easy to have awareness of others which can improve communication, and to move between focusing on their individual work and group work. Collaborators can also easily bring their own externalisation tools (such as computers and notes) into the meeting and share them amongst each other, which helps establish a common ground.

The different immersive technologies available for face-to-face collaboration may also provide unique benefits. For example, with a co-located Augmented

Reality interface each user has their independent view into the shared dataset that can be customized according to their role [109]. A virtual terrain model could be overlaid with sensor data for an environmental engineer, but an urban designer looking at the same AR model might see traffic information overlaid on the terrain. Similarly, using a tablet at the same time as an interactive wall [97,140] or table [134] allows the user to have their own custom private view and input into the shared display space.

8.3.2. Distributed Synchronous Collaboration

Many collaborative analytics tasks are performed by distributed teams, so there can be a need for Collaborative Immersive Analytics applications that support remote synchronous collaboration. For example immersive virtual reality displays can be used to allow analysts working at different locations to come together in the same virtual space to jointly explore complex datasets. Donalek *et al.* [31] describes how the OpenSim framework was used to create an immersive collaborative visualization space that could be explored in VR head mounted displays (Figure 6). Similarly, high-speed networking can be used to bring remote collaborators into an environment with interactive walls or tabletop displays. For example, the Hugin framework [70] allows the creation of visualization systems where a group of people around an interactive table at one location can connect and collaborate with users around a similar table at a remote location. Other systems have explored the use of mobile devices [88], web browsers [5], CAVEs [66] and Augmented Reality [138] for supporting remote collaboration for information visualization.

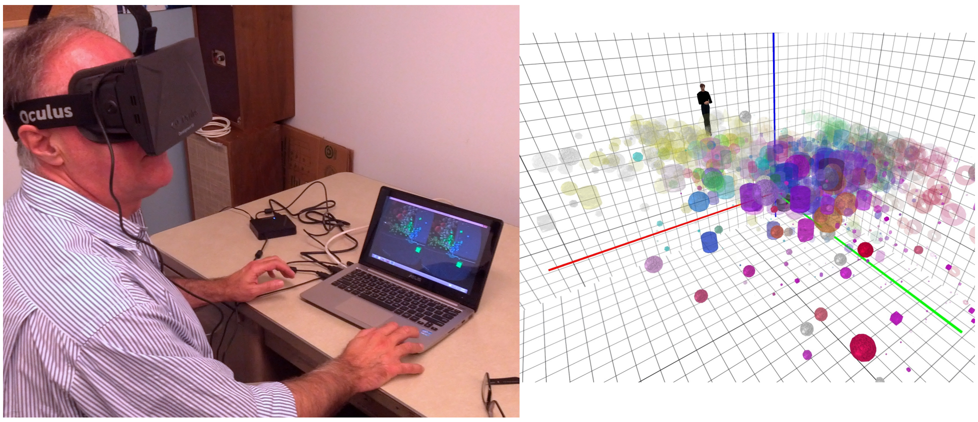

Fig. 6: Using VR to support remote collaborative data visualization, from [31]. User in VR HMD interacting with the system (b) VR view showing remote collaborator as virtual person.

The main advantage of synchronous remote collaboration tools is that they allow remote individuals to connect and collaborate together. In some cases this can produce a similar performance as face-to-face collaboration. For example, in a study comparing performance on a collaborative visual analytics task in a CAVE (face-to-face) or VR HMDs (remote), researchers found that searching in the HMD condition was as accurate as in the CAVE, and was completed faster [28].

However, there are significant challenges that need to be addressed around awareness and representation of each of the collaborators. For example, traditional video conferencing does not produce the same conversation style as face-to-face interaction [47]. This is because video conferencing cannot adequately transmit the rich non-verbal signals so vital in face-to-face communication and this introducing a communication seam between the participants [61]. In interactive walls and tables, the presence of remote collaborators are often reduced to a pointer icon [43], or virtual shadow of a hand [122]. Collaborative virtual environments immerse users in the same virtual space, but even here the remote participants may be reduced to simple video textures [46] or avatars that cannot convey subtle body motions [31].

Gutwin and Greenberg point out that designing for collaborative systems is difficult because of having to support two goals; designing for individual control over the application and designing for group awareness [43]. They say that collaboration in remote groupware tools is different from co-located collaboration for the following reasons: Groupware systems show far less of the workspace than what can be seen in a physical environment. Manipulation techniques in virtual workspaces are not bound by the physical constraints that exist in physical workspaces. Virtual workspaces can represent and display artifacts in more ways than physical workspaces allow.

8.3.3. Distributed Asynchronous Collaboration

For Immersive Analytics most collaborative applications involve synchronous collaboration. Viégas and Wattenberg point out that in general ”synchronous collaborative scenarios have been much more widely explored than asynchronous visualization based communication” [131]. However, distributed asynchronous collaboration involves capturing input from people at different times and different places and so can provide some unique benefits. For example, Benbunan-Fich *et al.* found that asynchronous collaboration can produce broader discussions and more complete reports from group discussions than their face-to-face counterparts [9]. Other benefits include enabling people to contribute whenever they have time to provide input [104], they can work on the part of the problem that they feel most qualified to address [129], and can combine information from a variety of sources [52].

Some efforts have been made to add support for asynchronous collaboration to CAVE and immersive Virtual Reality experiences, mostly through simple recording and playing back of messages. For example, Imai’s V-Mail system allows people to send and view asynchronous messages in VR [54]. In this case the user can record a voice message along with their virtual avatar body movements and gestures for later playback. Later, this was extended to include a VR-annotator tool for attaching 3D recordings to objects, and a VR-vcr streaming recorder for recording all actions occurring in a collaborative session [55]. Similarly, the Virtue immersive visualization environment provided support for multimedia annotations that allowed users to mark temporal and spatial points for later replay and sharing [111]. More recently, the vAcademia Virtual World shows how 3D recording can be used for asynchronous collaboration in desktop VR environments [89].

There are other examples of non-immersive asynchronous Analytics interfaces that can provide valuable lessons for extending this work. Zimmer and Kerren introduced OnGraX [143], a collaborative synchronous and asynchronous web based tool to support visual analysis of networks. Willet *et al.* have developed CommentSpace, a collaborative visual analysis tool that allows analysts to annotate information visualisations [136]. The tool allows analysts to add comments or view tags to the visualization over time and link the tags together to aid understanding of the document. In this way Collaborators gain the benefit of seeing the tagged classifications that people are applying to the text, and the semantic links being created. Similarly, Chen *et al.* [22] developed ManyInsights, a web-based tool for asynchronous collaborative analysis of multidimensional data (see Figure 7). Using this tool people can record their own insights from data, and read the insights of others over time. They found in an evaluation that this led to the generation of more shared insights, and being able to group insights by data similarity was a particularly powerful way to understand the data.

Heer and Agrawala [48] provide an excellent description of design characteristics for asynchronous collaborative visual analytics interfaces, drawing on web-based interfaces. In particular they list design considerations that should be taken into account, such as the value of supporting freeform annotations, using visualization bookmarks, linking to specific views, and clearly showing past actions that have taken place, among others. They designed the sense.us web application for social visual data analysis, showing how these design guidelines can be used [49]. In this case the interface supports view sharing, doubly linked discussions, graphical annotation, collecting and linking of views, awareness and social navigation, and unobtrusive collaboration. Figure 8 shows the sense.us interface and collaboration features.

Viegas and Wattenberg highlight the research opportunities available in the Distributed Asynchronous Collaboration Space [131]. They say "By not fully exploring asynchronous communication of visualization discoveries and processes, the research community is missing an opportunity to make important contributions to visualization research". In particular, they identify three features that are important; (1) Playback: Allowing users to edit a visualization session, picking out only a few key frames, and sharing it with someone else who can rewatch it. (2) Annotation: Enabling users to point to objects and add information. Tracking changes in annotations over time, and supporting group creation. (3) Information Foraging: Supporting how users spread their attention over the

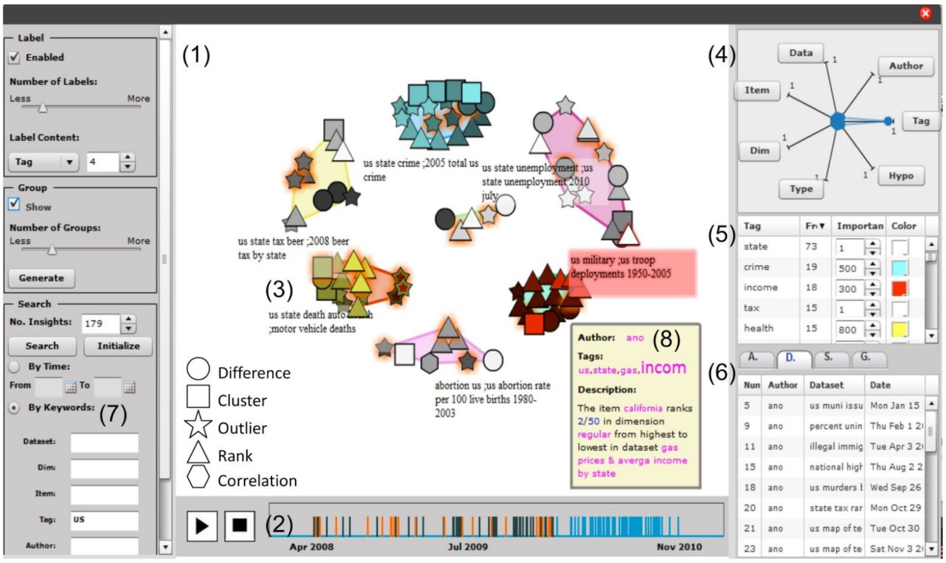

Fig. 7: ManyInsights User Interface [22].

data space, and encouraging users to look at little viewed parts of the dataset. We discuss more about the research opportunities in Distributed Asynchronous Collaboration in Section 8.6.

8.3.4. Co-Located Asynchronous Collaboration

Another area which has not been well studied for information visualization is co-located asynchronous collaboration. One common example of an asynchronous collaboration tool is a shared public display that people can view at different times. For example, Carter *et al.* [19] describe a public display interface that they developed for showing common topics of interest among emails and the current locations of the email writers. This display was designed to encourage more collaboration between co-workers. Other examples of using collaborative public displays include Groupcast [84], CWall [114], and the Notification Collage [40]. Figure 9 shows the Notification Collage interface with a variety of different media items (web pages, notes, video feeds, desktop views, etc.) posted on a shared public display.

The availability of public displays has prompted researchers to experiment with asynchronous, co-located visualizations, for example, in the form of ambient information displays [113]. In this case, public displays in the physical environment are used for information visualization. Pousman and Stasko [100] provide a good overview about how such systems can be used for casual information visualization in a public setting, such as showing bus timetable information, social networks,

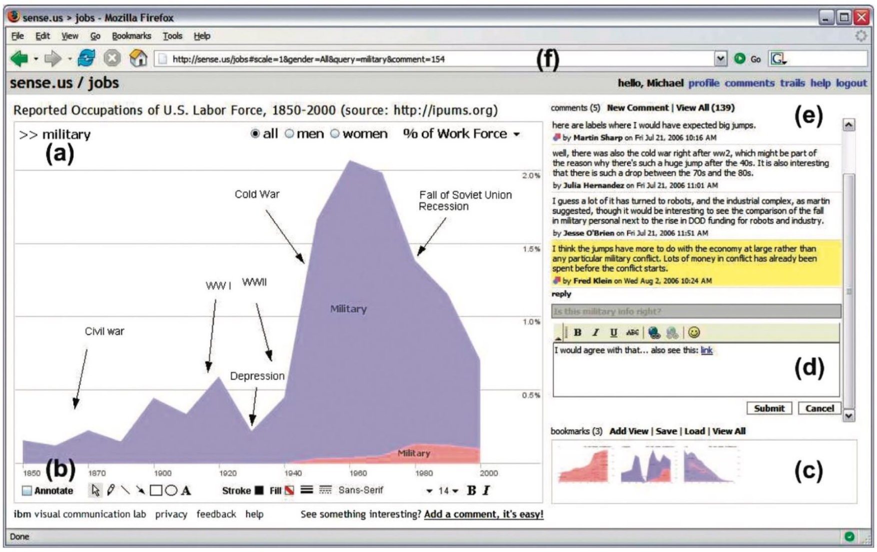

Fig. 8: Sense.us interface [49]; (a) an interactive visualization applet, (b) annotation tools, (c) a bookmark trail of saved views, (d) text-entry field for adding comments, (e) threaded comments attached to the current view, (f) URL for the current state of the application, updated automatically as the state changes.

or photo collections. Similarly, Vogel provides an overview and design guidelines for interacting with co-located displays [133].

Co-located asynchronous collaborative systems have many of the benefits of distributed systems, with the additional benefit of collaborators viewing the same physical space. Viegas and Wattenberg [131] mention that this offers some interesting design opportunities for the physical surroundings around the visualization, such as providing pens and paper for people to add their own notes around the display. Heer and Agrawala [48] point out the value of collaborators being able to see the same collaboration space, and other researchers have identified the value of having externalization tools that help people create and add their own insights [81]. Overall, having a common physical reference space with shared visualization and external objects should significantly help collaborators achieve common ground and shared contextual understanding [25].

8.3.5. Mixed-Presence Collaboration

So far we have talked about collaborative experiences that fit into only one quadrant of the time and space taxonomy. However, it is also possible to create experiences that link together two or more quadrants. For example, Mixed Presence Groupware (MPG) systems are collaborative systems that connect both co-located and distributed collaborators [53] [120]. As such Mixed-Presence

Fig. 9: The Notification Collage interface [40].

systems support synchronous collaboration between people in the same location and a remote location (see Figure 10). For example, the NICE Project supported collaboration between groups in one immersive CAVE with remote collaborators in other VR environments in an educational setting [67]. Other examples include interactive tables that include local and remote participants [106], and combining a VR conferencing space with a physical interactive table [103]. Figure 11 shows a typical mixed presence tabletop application where remote users are represented by video shadows of their arms (from [Tuddenham 2007]).

MPG systems combine the advantages of co-located and distributed synchronous collaborative interfaces, allowing distributed groups of people to work together. However there are a number of design challenges that need to be addressed. For example it can be challenging to enable co-located and remote users to have the same level of mutual awareness, and there is a need to provide some representation of the remote users into the local users space [98]. For example, video arms [121], as seen in Figure 11, can show where the remote users are reaching into the shared interactive space. It is also difficult to enable users to share notes, their own device screen and other local physical artifacts with remote users. Robinson and Tuddenham provides a list of design guidelines to address some of these challenges [106].

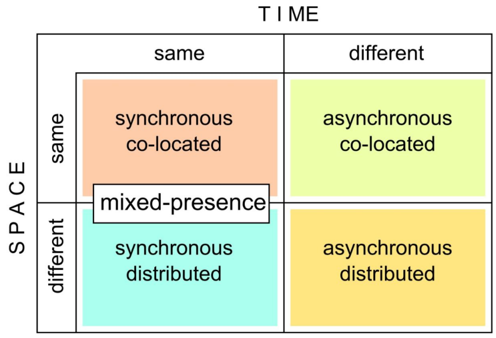

Fig. 10: Mixed Presence Groupware systems combining co-located and remote groups.

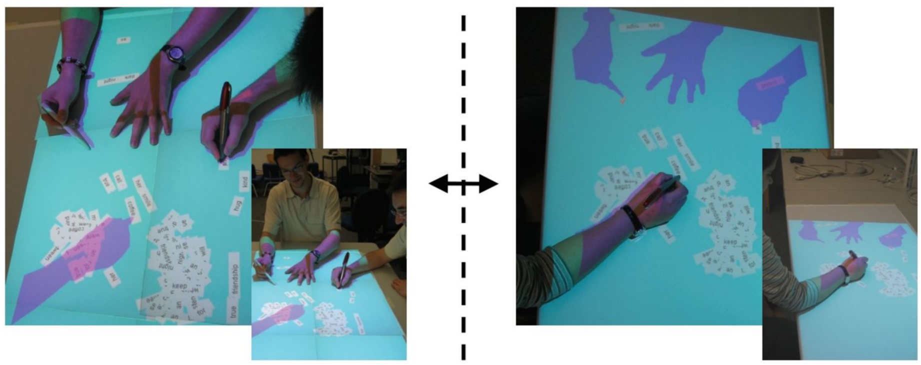

Fig. 11: Mixed Presence Tabletop System [106].

8.3.6. Lessons Learned

A number of lessons have been learned from this research. From the co-located synchronous research (e. g. [82]) the following features were found to be important:

- Supporting different independent viewpoints
- Enabling the use of different tools for different data
- Supporting face-to-face group work
- Using different data representations

Churchill *et al.* [24] reviewed a wide range of collaborative settings and state that the following should be provided in order to support good group communication and problem solving:

- Shared context - the shared knowledge and context around the data
- Awareness of others - users being aware of others' actions

– Negotiation and communication - people being able to freely talk with each other
– Flexible and multiple viewpoints - showing different viewpoints depending on roles

As can be seen from the reviewed systems, there are a wide range of different ways to achieve these requirements. In addition, previous research has shown that groups need to be able to have access to externalization tools, such as notes or laptop computers that enable them to record their insights and organize the results of their analysis [80] [48]. It is also important to enable collaborators to have access to both individual and shared workspaces [43] [60], and to enable them to easily shift their focus from their own work to the work of their collaborators [32]. Marai *et al.* point out that people from different backgrounds want to see data represented in different ways, so there should be multiple representations available and a variety of tools for interacting with the data [82].

In this section we have categorized collaborative systems according to how they support collaboration through space and time. Another important element of these systems are the various roles that the users have, and how the technology can support these roles. In the next section we describe the different roles used in CIA systems.

8.4. Types of Participants in CIA

In collaborative systems participants may have different roles or types of engagements with the system. For example, during a data driven presentation there are typically one or more people presenting while other constituents are audience members that generally do not interact directly with the presentation material. The roles of the people in the collaborative setting define the level of engagement that they have. Isenberg *et al.* [58] discuss how there are three different levels of engagement with collaborative visualization systems:

– Viewing: people are consuming a data presentation without interacting with the data, such as in a lecture presentation.
– Interacting/exploring: people have the means to choose alternate views or explore the data.
– Sharing/creating: people are able to create and distribute new datasets and visualizations to be explored.

Zhu [142] discusses role-based collaboration and points out that for efficient collaboration there needs to be support for asymmetric expertise and authority. For example, in a meeting the collaborative system needs to allow a presenter to control the image presentation, while the images shown should be made visible to all of the viewers in the audience. Similar to theater acting, storytelling can be enhanced by adjusting your presentation to suite your audience and react to their response. Sole [116] points out that effective knowledge-sharing requires storytellers to streamline their narrative by removing (or temporarily hiding) preparatory parts of the analysis that may overwhelm or confuse the audience. Sole asserts that the other most essential part of a good narrative is to provide a surrogate experience for the recipient. Immersive Analytics uniquely offers a sensorial advantage for enveloping recipients in a story thereby increasing the effect of Suspension of Disbelief. For example, analysts within a CIA willingly interact with abstract visualizations of data that may not realistically represent the original source of that data.

Collaborative Immersive Analytics builds upon these archetypal roles, but also enables the ability to mix roles. Given that CIAs are necessarily more highly mediated and interactive than traditional visual analytics platforms, it may be quite natural for participants to switch back and forth between passive viewer and active explorer. In fact, Heer *et al.* [49] discuss how their sense.us platform was a social space for information visualization designed to facilitate data driven discussion and debate. CIA offers a unique opportunity for example in Command and Control scenarios where users may spend most of their time monitoring data feeds and then switch contexts into active analyst and explorer roles as problems arise. It is thus important that data representations and interfaces of CIAs can support fluid transitions between these roles. Another consideration when designing Collaborative Immersive Analytics is the number of creators and consumers. Here are some of the most common formats for collaborative analytics:

- One to self (e. g. data discovery that might be shared later)
- One to some (e. g. reporting findings to colleagues)
- One to many (e. g. presenting reports to stakeholders)
- Many to many (e. g. department heads presenting at employee town halls)
- Many to one (e. g. department heads presenting to CEO)
- Machine to one, some or many (e. g. AI returning results to analyst)

Up until about 10 years ago, the predominant method for analysis was through a guided analytics approach whereby data scientists created visualizations that were presented to and utilized by other users. In the Business Intelligence industry, this meant a very small group of individuals produced highly structured dashboards and reports which were consumed by specific departments within large organizations. Over the last 10 years though, there has been a massive shift to what is referred to as Self-Service Analytics in which users now have the ability to input, access, and analyze data directly by themselves. This transformation has enabled a new form of data discovery which allows for more people to ask more questions and solve more problems. This trend towards creating new collaborative analytics platforms is nicely articulated by the ManyEyes project [132] mentioned earlier. ManyEyes attempted to “democratize” visualization by not only serving as a discovery tool for anyone with data, but also as a platform to prompt discussions around data for large groups of users. This example best typifies the “many to many” form of collaboration.

Machine learning and artificial intelligence (AI) are being applied more and more towards analytics. There are many advanced analytics systems which employ

AI to automate various aspects of the analysis process including everything from data cleansing, preparation and modeling, to dynamically creating visualizations or data-driven narratives through natural language generation, to alerting users of “unusual activity” and predicting future trends. This new “analytics agent” can be considered as a third axis in a collaborative user matrix in Figure 12. Within a CIA, this collaboration with the AI could be represented through a friendly 3D avatar such as those we already interact with aurally through automated voice systems. However, ultimately AI systems will likely mature sufficiently so that they will replace some human knowledge workers through new forms of deep learning combined with expert systems.

This possible introduction of machine intelligence in the analysis process complicates further the design of CIA, as it adds a new level of complexity in the form of an additional actor or role (beyond the existing human ones), whose actions need to be made aware and interpreted by the human collaborators.

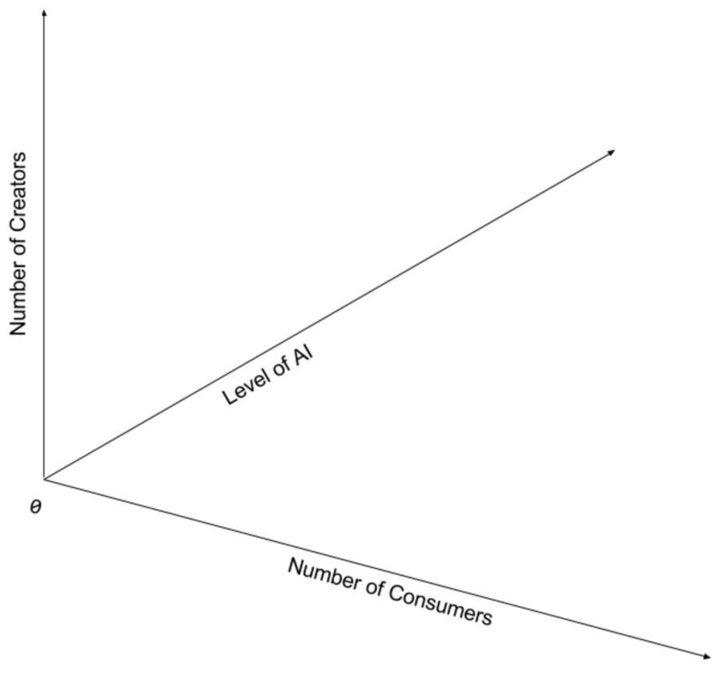

Fig. 12: Collaborative User Matrix.

Given that CIAs can offer more interactivity and potential for greater contribution by more participants, it can also encourage dialogue and debate around data analysis. If a chart is presented in 3D and one can easily move around it and interrogate it, will that simple shift in perspective also transform users into active listeners? Or can we go beyond simply allowing for the ability of multiple users with various roles within an Immersive Analytics environment to also enable them to have suitable means to effectively collaborate? In the next section we will explore how different types of interaction modalities enable participants within a CIA to engage in various analytic tasks.

8.5. Interaction in CIA Environments

Deciding on appropriate interactions to support any visual analysis task is important, as interactions facilitate the dialogue between analysts and their data [126]. When considering collaborative environments in particular, analysts are in dialogue not only with the data, but also with each other, and the choice of interaction technique can influence the nature of collaboration and the awareness of others [32,44]. For example, Prouzeau *et al.* [102] observed that when analyzing graphs on a wall display, pairs using techniques with a large visual footprint adopted tighter coordination strategies than pairs using techniques that were more visually localized.

Interaction design in Collaborative Immersive Analytics (CIA) environments faces similar challenges to other visual analysis environments [126]. For example they require *interactions to support potentially complex analytic tasks*, such as defining and filtering unwanted data, requesting new representations of the data, etc. The chapter on interaction covers these extensively (Chapter **??**). Thus the interaction vocabulary in such environments needs to be rich enough to go beyond simple actions such as pointing (a task studied in detail in immersive environments). Moreover, collaborative environments must also take into account other challenges and opportunities identified in previous work on collaborative immersive environments more generally.

This section discusses preliminary *synchronous* interaction (co-located or distributed), as it directly impacts collaboration aspects such as awareness and coordination.

8.5.1. Synchronous Co-located CIA

Synchronous co-located CIA happens historically in shared **physically large** immersive environments such as CAVEs, walls and multi-display environments (MDEs) that surround the viewer, where analysts can *move freely around the space* (such as the ones seen in Figures 1 and 5). Movement has been linked to benefits such as avoiding occlusion by others in CAVEs [21], and correcting for possible visual distortion in walls [13].

Movement: While collaborative interaction from stationary positions with mice and keyboards is still possible [16, 57], it does not leverage the full rendering capacities of these immersive environments. In CAVEs analysts can move inside the data itself and view it from different perspectives. With walls they can see data at different scales, coming close to the display to see details and further back to get an overview [7]. With tables, they can see data from different angles by moving

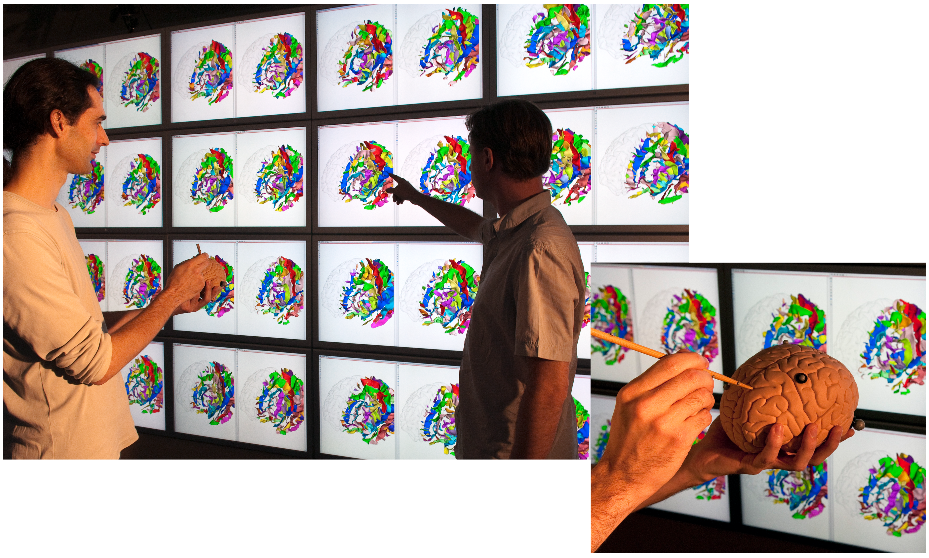

Fig. 13: Interaction using a tangible prop of a brain to rotate brain images, and a stick that defines the camera position (left), and close-up (right) from [39] (used with permission, ©CNRS-Phototheque - Cyril FRESILLON).

around the table. In all cases, movement can be seen as an implicit interaction for navigating in the data space. Movement has also been used as an explicit interaction, for example to trigger dynamic changes in content rendering [7], or to invoke actions such as dynamic filtering depending on the analyst's position and movement [63]. While such approaches can increase the interaction vocabulary, they need to be carefully considered in collaborative environments, where implicit actions as simple as moving may cause large scale visual changes that could disturb other analysts. This issue is particularly prominent in large-scale stereoscopic environments (such as CAVEs), where almost always only a single person controls perspective and interaction, even though multiple people can move in the space.

Pointing and Gestures: Existing work has looked at different interaction alternatives that support free movement. Research on CAVEs, walls and multi-display environments have considered extensively pointing techniques (using hands or dedicated devices) [4, 92, 93], that combined with on-screen menus and widgets, could cover the complex interaction needs in CIA environments. Pointing actions can be easily seen by colleagues, increasing the awareness of others. Nevertheless, the existence of persistent on-screen menus on the shared collaboration space takes up space that could be used for displaying data, while menus invoked on the fly can be disruptive to collaborators sharing the space.

As an alternative, hand or full-body gestures can activate commands (e. g., [117]) and provide a rich interaction vocabulary without taking up screen space. They provide awareness of the actions of others, given that these gestures are

Fig. 14: Multi-touch input on a tablet to zoom and scroll through a stack of brain-scans [97] (used with permission).

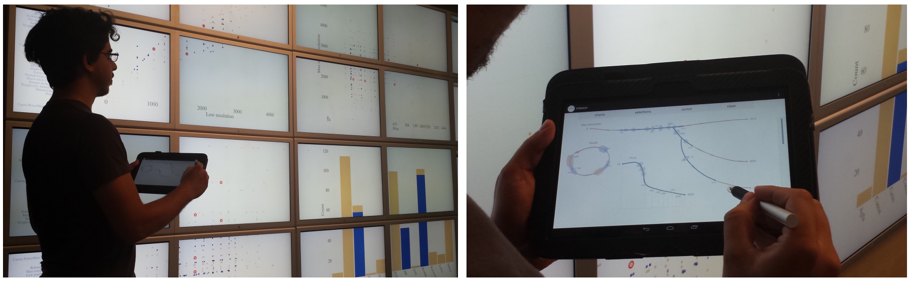

Fig. 15: A user sketching the sliders they need for their exploration [127] (used with permission).

easily seen by colleagues sharing the space. Nevertheless, full-body gestures can prove tiring during long periods of work [139] required by some analytics tasks [126], and gestural vocabularies can be large thus coming with a learning cost [69].

Dedicated Devices: Researchers have also examined the use of personal, dedicated, or generic, mobile devices. For example, in order to analyze brain scans on a wall display, Gjerlufsen *et al.* [39] suggested using a dedicated tangible prop of a brain to rotate and translate the scans (Figure 13), and physical tools to indicate camera viewing directions; Olwal *et al.* [97] suggested using dedicated software running on tablets to provide interaction tools and different views of the brain between colleagues in medical teams (Figure 14).

These examples illustrate the large possible range of such mobile devices in terms of both generalizability across analytic tasks, and awareness of others. Interaction with dedicated tangible props (such as a model of a brain), comes with a high degree of awareness since props used by colleagues are easy to identify, but their utility is limited to specific data domains and analysis tasks (exploring brain scans). On the other hand, more general purpose devices can be adapted across analysis tasks and data. For example, devices with multiple degrees of freedom (e. g., [11, 37]) allow for a rich input vocabulary while at the same time being general purpose. Existing mobile devices, such as smartphones and tablets, can also be appropriated, adapting their content to provide a personalized interface

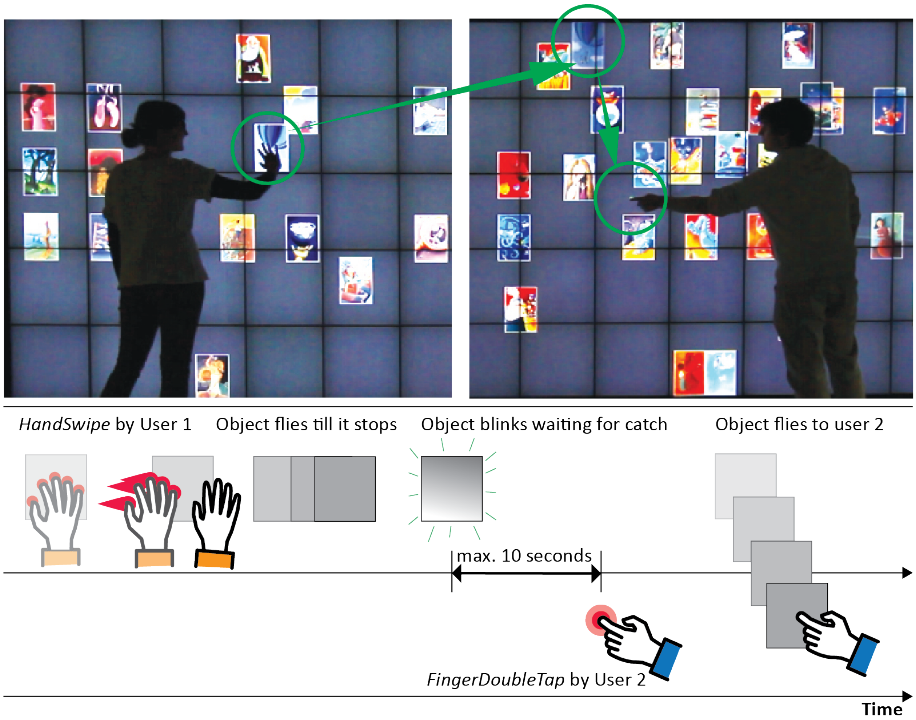

Fig. 16: A user throws an item and another performs a gesture to make it "fly" to their location in CoReach [79] (used with permission).

for analysis tasks or personal views of the data [97,134,140]. Mobile devices can also be combined with physical widgets [64] or be customized by analysts, for example allowing them to sketch their own interfaces based on their analysis needs [127] (Figure 15). Because these more general purpose personal devices can be adapted to help analysts perform many tasks, they usually provide limited awareness of the actions of others. In this case, additional awareness information needs to be given during collaboration, for example in the form of colored cursors, or other highlights to indicate the work of others [44]. Mobile devices, dedicated or general purpose, need to be carried around while analysts are moving, which could prove cumbersome in long duration analysis tasks.

Touch and other modalities: Physically large immersive environments often include displays that can act as touch surfaces. In the past researchers have considered direct touch interaction as input in collaborative analytics on very large surfaces such as walls [62,102] or tabletops [60,91]. Direct touch provides immediate awareness information about where others are working in the shared space, and allows for direct manipulation [112]. Nevertheless, touch technology may not be always available, and even if it is, it requires users to be close to the display, missing the benefits of movement discussed before. This is where multi-modal interaction can prove useful; for example Liu *et al.* [79] use a collection of collaboration techniques based on direct touch on a wall and distant interaction using mobiles. More generally, multimodal interaction can prove beneficial for collaborative settings for diverse reasons. For example, adding voice commands on a touch tabletop can enhance the gesture vocabulary and potentially increase awareness of others' actions [128]. Or providing personal devices coupled with the shared interactive surface, allows colleagues to fluidly move between individual and team work [110], and chose when to share their individual analysis results with others [85].

Collaborative actions: Co-located collaborative settings also allow the creation of new collaborative interaction techniques, where users combine their actions in order to create a single more powerful interactions. Morris *et al.* [90] present actions by multiple colleagues that the system interprets as a single command, in order to pass ownership or trigger global changes for example. Tse *et al.* [128] allow colleagues to combine verbal commands on a tabletop to group objects. Isenberg and Fisher [59] provide collaborative brushing and linking interactions on tabletop visualizations and Liu *et al.* [78,79] look at how multiple collaborators can share actions such as moving objects across different areas on a wall display (Figure 16).

8.5.2. Synchronous Distributed and Mixed Presence CIA

Synchronous **distributed immersive** technology, such as HMDs provides analysts with the ability to *chose whether to share exactly the same view or completely different ones.* As with individual analysis in these environments (see Chapter **??**), a rich input vocabulary can be achieved using pointing and virtual menus [15], more elaborate gestures [6, 26, 74], or even mobile devices [36]. What is unique about this setting is that, contrary to physically large environments where awareness of others often comes from seeing the location and actions of others within a shared physical space, here analysts may be unaware of the focus and view of their colleagues. In order to maintain awareness of others, interaction needs to provide feedback not only to the user taking an action, but also to their colleagues. For example, researchers have proposed the use of avatars to represent their fellow analysts within the virtual world, starting from very abstract representation of others [10] to full 3D body models [101]. Analysts' actions need also be accompanied by feedback presented to their colleagues, for example in the form of highlights of their area of focus [38] that can be very fine grained (e. g., through eye-tracking [42]), and the ability to share views with others [96].

Given the introduction of **augmented reality** technology, it is possible to have scenarios where *analysts are physically co-located, but have personal views* of their data superimposed on the virtual environment. In these mixed reality environments, most interactions that are possible in physically large environments are possible here as well (with the exception possibly of touch interactions on shared surfaces). Nevertheless, in this context, awareness of actions can prove problematic. Even if the physical position of analysts and their physical actions (e. g., gestures) are visible, there is no guarantee that they are transparent to their colleagues since they are not sharing a common view. This problem is similar to the awareness challenges present in distributed environments. It may even be more pronounced in mixed reality settings: in distributed situations, representations of colleagues can be artificially placed close to their areas of focus; in a mixed reality setting, we have a strong visual presence of colleagues moving inside an analyst's field of vision (but not necessarily sharing a common view), that may be hard to override in order to represent their virtual focus.

Designing interaction for situations where some colleagues are co-located and some distributed, i.e., **mixed-presence** collaboration, presents possibly the biggest challenge. The analysis environment needs to provide awareness support for the actions of co-located colleagues, while at the same time providing representations of the distributed partners and/or their actions. All this, in an environment that is likely already occupied by large amount of visualized data.

8.5.3. Asynchronous CIA

So far, we have considered only synchronous interaction in collaborative environments. Nevertheless, analysis tasks can be long, requiring several work sessions [126], or analysts may work individually but share their analysis later on. These asynchronous analysis sessions can be done either distributed, or even co-located (working in shifts). In these case, some interaction challenges are similar to single user interaction. Nevertheless, there are new problems that arise when analysts **work asynchronously**, such as understanding where their colleagues left-off with their analysis, where they focused on, etc. More general, supporting hand-off in asynchronous analysis [141], both co-located and distributed, becomes crucial. Here, we require techniques that leave a trace of the analysis work and progress of colleagues. These can be explicit, for example annotations or summaries left behind for others [94, 105]; implicit, such as summaries of all past interactions (as is done in [14]); or a combination of both, where the analysis system can help the analyst to tell a story [18, 34, 75, 107] of their work to bring their colleagues up-to-speed (see Chapter **??**).

8.6. Opportunities for Research

Collaborative Immersive Analytics is an emerging research field and it is still underexplored. As it is challenging to identify a pertinent path to explore in CIA, this section aims to provide a non-exclusive list of important research questions to guide research in this new domain. Previous work has identified important characteristics of Collaborative Visual Analytics. Heer [48] identified the following topics to explore:

- Division and allocation of work
- Common ground and awareness
- Reference and deixis [1]

[1] Deixis refers to words and phrases, such as "me" or "here", that cannot be fully understood without additional contextual information. Source: Wikipedia.

– Incentives and engagement
– Identity, trust, and reputation
– Group dynamics
– Consensus and decision making

Virtual/Augmented/Mixed reality, wall-size displays and tabletops can lead to more immersion and presence. The nature and affordances of such *immersive environments* may have an influence on how a group of users work together. This chapter presents a set of questions related to the space/time matrix and important topics previously identified in Collaborative Visual Analytics, with respect to immersive environments.

8.6.1. Virtual reality for Immersive Collaborative Analytics

CAVE-style setups and large display or multi-display environments are a natural space for collaboration. CAVE-style setups are rooms with screens surrounding the users. Collaborators view and talk to each other, and can, for example have face-to-face discussions. Collaboration in Virtual Reality can also be alternatively supported by networked head-mounted displays, or fishtanks. Cordeil *et al.* [28] found that performances were comparable between CAVE-style displays (Figure 17) and HMDs (Figure 18), but raised some usability issues for collaboration. However, there are other Virtual Reality displays that need to be compared for collaboration. Hence it is important to conduct research with different display form factors.

8.6.2. HMDs and face-to-face communication

While HMDs offer an alternative to wall displays and other CAVE-style environments, they obscure the face of collaborators. This can potentially be a major impairment as facial expressions are used as visual cues for different reasons, including establishing a common ground or assessing and discussing findings [48]. The study of Cordeil *et al.* [28] did not reveal a major issue with this impairment but they tested only low-level graph visualization tasks and did not test analytical reasoning. In this condition, using only conversation and gaze was probably sufficient to complete the tasks. An interesting opportunity for research is to measure the effect of not seeing the face expressions of collaborators:
– When they are sharing insights: how does it affect engagement?
– On the group dynamics: how does it affect leadership?

8.6.3. CIA and scale: number of users

Research has often studied collaborative tasks with head-mounted displays or shared large displays, involving only two collaborators. In real-life applications, collaboration potentially involves larger team sizes. There is a compelling case to study the impact of using both HMDs and shared displays, such as walls and tabletops, with large groups in terms of situation awareness. In order to design and develop future techniques, systems and platforms that support immersive and collaborative analytics, it is crucial to study how different group sizes collaborate with visualizations. A possible (non-restricted) list of research questions related to group size, could be:

– How do collaborators locate each other's positions in collaborative virtual environments?

– How do collaborators share insights with others (either in virtual or collocated environments)?

– How do collaborators share/find each other's cues?

8.6.4. Distant Collaborative Immersive Analytics

Little research has been focused on remote collaboration using immersive display technologies. Some studies have been carried out in the scientific visualization domain [31] and the robotics domain [73]. Those studies often investigate the ability of users to perform their tasks in such environments, and often use artificial or abstract tasks such as puzzle solving. However, collaborative analytics requires a higher level of engagement from collaborators when analyzing and understanding data. The study of engagement of team members in remote, immersive and collaborative data analytics remains widely unexplored. To this regard, the following research questions should be investigated:

– Does immersive and collaborative analytics bridge the distance gap in remote collaboration scenarios?

– What is the impact of immersion in collaborative analytics quality?

– What is the effect of immersion on remote collaboration: engagement, group dynamics?

8.6.5. The design space of Immersive and Collaborative Analytics

Immersive display technology is very heterogeneous. It includes head-mounted displays, CAVE-style environments, wall-sized displays, tabletops, and multi-display environments. Those displays also vary widely in size, resolution, and modality of interaction. Choosing which technology is more appropriate for the given tasks and needs of analysts, and designing for them, is a challenge. There is a great opportunity for research to define the design space of collaborative immersive analytics in order to guide the design of immersive collaborative platforms. Moreover, we can envision situations where a mix of these technologies can come in play, for example a group of analysts working in a CAVE and a colleague connecting remotely using a HMD. Understanding how collaborative analysis is affected by analysts using asymmetric technology (in terms of awareness, deixis, group dynamics), and how to design for it, is an important research direction.

8.6.6. Asynchronous collaboration

Collaboration can occur asynchronously for various reasons: collaborators work in shifts, in different time zones, they have different schedules, etc. In this situation, users view, analyze and understand data at different moments in time. We can identify two roles:

– A "hand over" role: users who have finished working with the visualizations

– A "take over" role: users who come after the previous group to keep working with the data visualization.

It is important to understand what the users' needs in those two roles are and how immersion can be used to better support hand-overs.

On one end, immersive technology can help preparing high fidelity handovers to communicate the results of data analysis. There are various ways to create a handover for the next users. For example, motion-tracking technology can be used to record precise hand gestures and interactions with the visualizations, and stereo cameras can record a user's body and face. Such recording can be used to facilitate telling a story (Chapter **??**) about the work done with the visualizations. However, telling a story is only one form of asynchronous collaboration handover. A group of users may require the help and draw the attention of another user or a group of users to examine a specific issue. On the other end, a user who enters a collaborative space needs to be updated with the situation. The tasks of this user can be to consult the handover, resolve issues, answer questions, provide input for a specific problem, etc. In the context of Collaborative Immersive Analytics, it is unclear which techniques are better suited for specific scenarios. Hence, there is a research opportunity to study how to convey the state of progress of collaborative visualization in immersive and asynchronous collaborative analytics.

8.6.7. Channels for collaboration

Collaboration between members of a team is supported by various channels of communication. Those channels include (but are not limited to) oral communication, gaze direction, deixis (e. g. pointing) or feedback from other members' actions. Since CIA can simultaneously occur across different types of immersive technology, it seems important to evaluate, according to the users' tasks, which are the essential channels to support efficient group work.

8.6.8. Evaluation of CIA systems

The evaluation of CIA systems, as with all collaborative visual analysis systems is a challenging matter, as it needs to consider both task-related and teamwork related aspects [56]. Because collaborative environments incorporate a large number of variables to consider, they are often evaluated through field and laboratory observation studies [56]. The variables to consider increase in immersive environments, as colleagues may have asymmetric collaboration, be joining the work with different immersive technology, making evaluation even more challenging. Recent years, have also seen an increase in controlled experiment evaluations in collaborative immersive environments (e. g, [79], [102], [20], [78]), where researchers try to tease out effects of particular factors, including immersive technology. For example, Cordeil *et al.* [28] compared CAVE environments to Head-mounted displays in a graph analysis task (Fig. 18,17). Clearly, it is a mix of

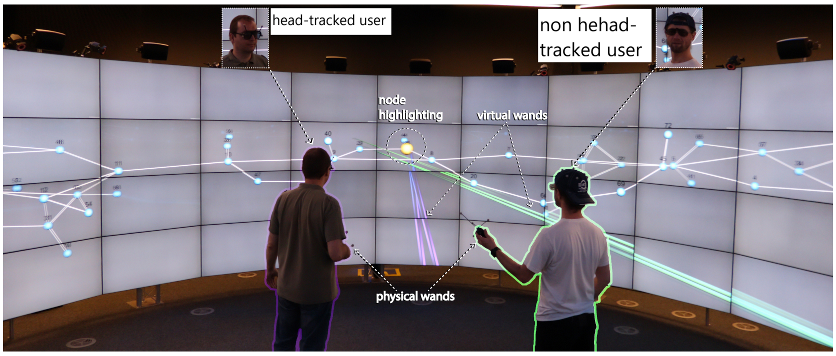

Fig. 17: Two users visualize a 3D network of abstract data in the CAVE2. The 3D immersive visualization can only be presented from the user wearing the head-tracker (left) [28] (used with permission).

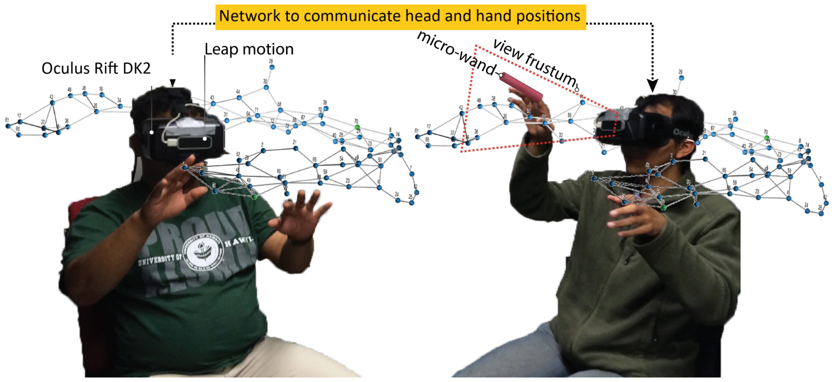

Fig. 18: Two users visualize a 3D network of abstract data in a network application with head-mounted displays. This platform allows independent head-tracking. Gaze cues and interactions are communicated on the network [28].

both open-ended and controlled evaluations that can provide practitioners with holistic insights. Hence, it is important to build evaluation frameworks for CIA, based on subjective, objective and collective measures to quantify the efficiency of collaboration. Such frameworks can certainly be built upon existing ones, for example ones coming from social presence [41].

8.7. Conclusion

This chapter introduced the concept of Collaborative Immersive Analytics (CIA), defined as the shared use of new immersive interaction and display technologies by more than one person, to support collaborative analytical reasoning and decision making. As shown in the introduction, CIA is at the intersection of the fields of Mixed Reality, Visual Analytics and CSCW and as such there are many technologies and approaches available for building CIA systems. These were classified according to a space-time taxonomy, and examples of systems in each quadrantof the taxonomy were provided.

From these examples we see some of the benefits of CIA systems, including enabling teams to work together, using emerging immersive technologies for intuitive data explorations, supporting multiple devices and tools, and seeing multiple representations of data. Perhaps most importantly CIA systems have the potential to enable teams to overcome the barriers of distance and time to collaborate together in the most effective way possible.

To fully realize this potential CIA systems must be carefully designed. The chapter covers the different roles collaborators have in such systems, such as viewing, interacting and sharing which should be accommodated in the system development. It also reviews the types of input modalities that could be used to design intuitive interaction. These include devices for capturing pointing and gestures, dedicated handheld devices, support for touch, and the use of collaborative actions involving input from multiple people.

While the individual domains of visual analytics, immersion, and computer mediated collaboration each have a long and rich research history, their combination that gives rise to CIA is very new and so there are significant opportunities for future work. As discussed, fewer than three percent of the papers published in the main visualization conferences even address collaboration. The chapter conclusion identifies a number of topics for research including using VR for CIA, developing methods for distant CIA, exploring the CIA design space, asynchronous collaboration, and methods for evaluating CIA systems. Perhaps most importantly is research in the area of multi-user interaction. Interaction modalities that may work well in immersive environments in general, are not necessarily appropriate for complex collaborative analysis work, that may last over several sessions, with participants connecting using different technologies. If and how technological asymmetry between colleagues can affect the quality of analysis work is still an open question.

Overall, Collaborative Immersive Analytics is an exciting new field with significant potential for improving how teams problem-solve, and presents many opportunities for ongoing research. CIA is at the same point that the field of visualization was at twenty years ago, and in the same way that visualization has become a key tool in the years since, we expect that CIA will dramatically change, and challenge, problem solving in the future.

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